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Initial Consideration of the Feasibility and Optimal Application of Tactile Sway Cueing to Improve Balance among Persons Suffering from Disequilibrium

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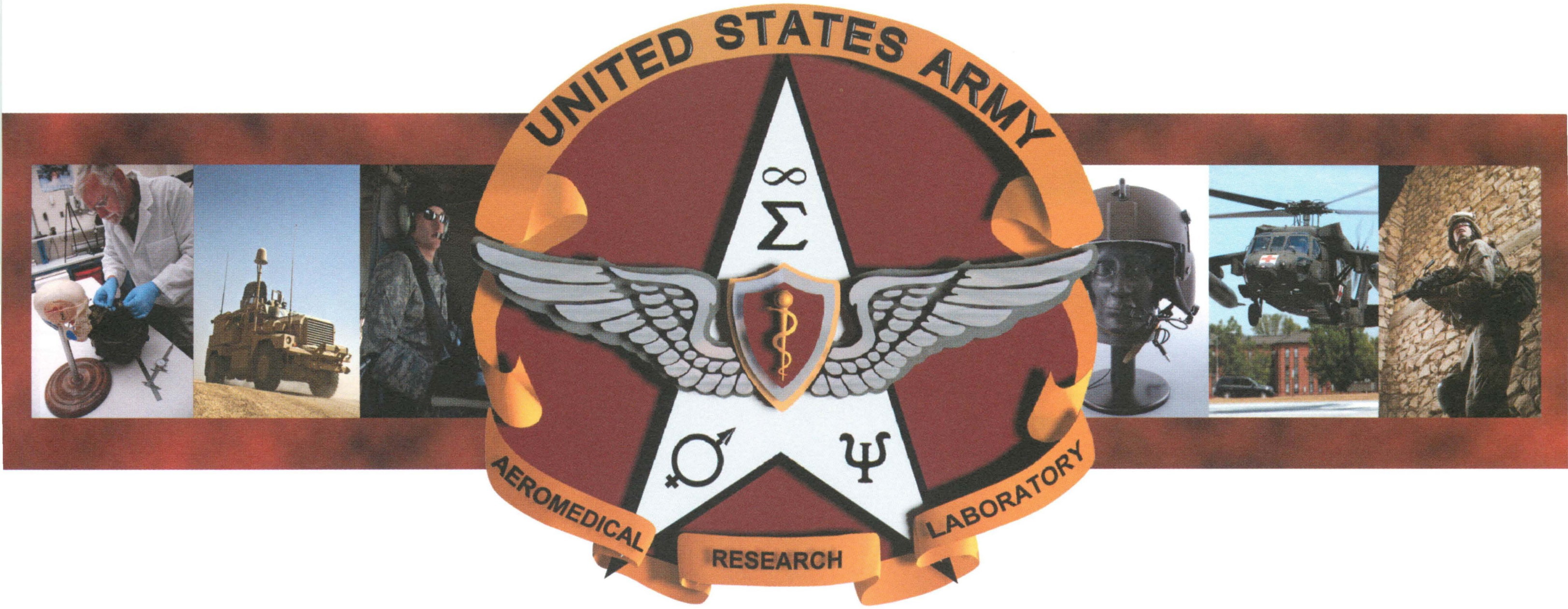

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14. ABSTRACT

This report explores the use of tactual sway cueing as a compensatory strategy for patients suffering disequilibrium. Sway feedback systems have the potential to aid Soldiers with traumatic brain injury (TBI) and other patients whose balance has been disrupted by concussions, labyrinthine diseases, or aging. Several sway feedback approaches are considered and recommendations are made concerning the steps necessary for the successful transition of promising approaches.

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Introduction

This report summarizes the findings from the U.S. Army Medical Research and Materiel Command (USARMC) project, “Using tactile cueing systems in traumatic brain injury (TBI) patient mental and physical rehabilitation.” The objective of this project was to explore three different systems for providing tactile sway cueing as a compensatory strategy for patients suffering from disequilibrium due to TBI. Partly based on the first author’s aviation-related research on the Tactile Situation Awareness System (TSAS) to prevent spatial disorientation, other investigators (e.g., Wall & Kentala, 2005; Atkins, 2009) have explored the feasibility of using TSAS-like systems to provide sway feedback to improve standing balance among patients experiencing disequilibrium (see this Introduction and the next section on Relevant Background Findings).

Rather than proceeding with a TSAS-based system as the default approach for tactile cueing, the first author wished to attain greater objectivity by consulting other experts and asking them to consider a TSAS-based cueing system versus two other available tactile sway cueing systems. That first group evaluation to identify the advantages and disadvantages of three sway cueing systems was the purpose of this USAMRC project, the outcomes of which are described in this report. This report describes a preliminary qualitative evaluation; further and more objective evaluations are in progress (see Conclusions and Recommendations).

To achieve the stated purpose of group evaluation of multiple possible alternatives to TSAS-based sway cueing, meetings were held with experts from the Veterans Administration, U.S. Army, U.S. Navy, and U.S. Marine Corps as well as researchers involved in the development of tactile cueing devices. The meetings sought to evaluate the best forms of tactile cueing to provide balance rehabilitation for brain injured Soldiers. Feedback from military physical therapy (PT) experts was incorporated into a plan for future efforts in diagnostics and rehabilitation, as well as Small Business Innovative Research (SBIR) to support the needed technologies and assist with transition for widespread use. The following report describes the outcome of these meetings and the best path forward. We start below with a brief description of the problem of disorientation.

The sensory systems we use for balance, orientation, and ambulation are the somatosensory (skin, muscle, joint), vestibular, and visual systems. In our day-to-day activities, these three sensor systems provide concordant, redundant, and veridical information concerning orientation. As Helmholtz pointed out in the 19th century, spatial awareness is designed such that each sense can “happily supply each other’s deficiencies” (Helmholtz, in Warren & Warren, 1968).

The situation changed when humans developed devices permitting them to enter the aerospace environment, where they lost the benefit of these redundant sensory feedback systems.Unusual graviotinertial forceenvironments are generated during aerospace operations, where vestibular and somatosensory cues are misleading and redundancy is lost, making spatial disorientation more likely. To fly safely in the aviation environment, we rely on inertial sensors to provide the information normally provided by the vestibular and somatosensory systems. The information from the aircraft orienting sensors is provided visually on an instrument panel and

must be attended to and cognitively interpreted. Many mishaps occur when pilots do not attend to the visual instruments frequently enough and make inappropriate control inputs, causing the aircraft impacts the ground.

On earth, orientation information is provided to our central nervous system at lower levels of awareness continuously and in a highly automated fashion. This permits us to carry out the very difficult tasks of walking and running with minimal cognitive effort. However, when patients suffer from sensory maladies (e.g., vestibular disease or injury), a similar failure of sensor redundancy occurs and disorientation is experienced. In fact, the disorientation experienced by balance patients has more rapid adverse consequences than that suffered by the disoriented aviator.

In 1993, an ear, nose, and throat specialist, James Atkins, M.D., (a former U.S. Air Force [USAF] flight surgeon) and a vestibular rehabilitation physiotherapist, Karen Atkins, Ph.D., realized the potential earthbound balance applications of my (Angus Rupert) research on spatial disorientation in flight, so they invited me to present my work to the balance community. My colleagues and I had developed a novel approach to reduce spatial disorientation (SD) mishaps in the aerospace community and assist with situation awareness (SA) by providing orientation information (e.g., aircraft attitude) through the sense of touch (Rupert, Mateczum, & Guedry, 1990; Rupert, Guedry, & Reschke, 1994; Raj, Suri, Braithwaite, & Rupert., 1998; McGrath, Estrada, Braithwaite, Raj, & Rupert, 2004). Our solution for the loss of aircraft control was to provide the orientation sensor information continuously through the sense of touch and utilize the tactile orientation reflexes developed over millions of years to maintain orientation intuitively, thereby releasing the cognitive demands of the visual system for other tasks. This system is known as the Tactile Situation Awareness System (TSAS). The TSAS concept was first presented in Copenhagen at a 1989 NATO AGARD meeting (Rupert, et al., 1990) and first flown in 1991 (Rupert, et al, 1994). Research by our group and others indicated that tactile feedback could improve spatial orientation in real and simulated flight (Rupert, 2000; Cardin, Vexo, & Thalman, 2006; Curry, Estrada, Grandizio, & Erickson, 2008; Brown, 2009).

Drs. James and Karen Atkins hypothesized that our algorithm for providing pitch and roll stability in aviation platforms could be applied to balance patients using center-of-gravity information from a balance platform. Determining whether this solution was feasible would contribute to the field of vestibular rehabilitation (Herdman, 1999) and constitute something akin to an “acid test” concerning whether TSAS is intuitive and rapidly interpretable, because the system would be tested not on select groups of healthy aviators who would have 2 to 30 seconds to react appropriately to prevent spatial disorientation, but on patients with severe balance problems whose compensatory reactions would have to be implemented within tens of milliseconds. Some earlier findings suggested that tactile cueing might work – these are described briefly below.

Relevant background findings

Circa 2003, as part of a Naval Air Systems Command (NAVAIR) project, we exposed subjects to a rotating room to look at adaptation and aftereffects associated with motion and synthetic environments. While the room rotated slowly (at 24 degrees per second [dg/s] or 4 rotations per minute [rpm]), the subjects made single pitch and roll head movements and walked from one chair to another chair before resting for 45 seconds. After 10 minutes, subjects began to adapt to the new environment, showing eye reflexes and coordinated walking movements appropriate to the new rotating environment. When subjects left the room to be tested on the balance platform and be compared to their performance prior to becoming adapted on the rotating room, some subjects reported that head movements felt "unusual" or "funny" and made them unsteady. The subjects did not demonstrate any pre- to post- performance difference on regular Neurocom Equitest Sensory Organization Tests (SOTs), but did on a modified version of the SOT 5, in which subjects close their eyes and move their heads while standing on a platform that measures their center-of-gravity and provides tilt of the platform in the direction the center-of-gravity is shifting. This test has since been incorporated by the manufacturer of Equitest into the software and is now used by NASA as an objective test to determine when returning astronauts are safe to fly (Jain, 2010).

Since we had tactile cueing devices readily available from the TSAS aviation projects, we performed a small pilot test on five experimenters. We placed tactors on rotating-room-adapted subjects (front and back of torso) and then provided center-of-gravity information from the platform to the front or back of the torso to indicate which way they were swaying. The subjects with tactile cueing could maintain upright posture while subjects without tactile cueing could not. Two important results were obtained from the initial pilot test: first, tactile cueing could be used reflexively to improve balance performance in compromised individuals, and second, adaptation to a rotating environment could be used to create a temporary, rapidly reversible, "acute vestibular insult". This pilot test was followed by a series of assessments conducted in cooperation with Dr. Conrad Wall and his student (at the time), Ms. Patricia Schmidt, and became the basis for subsequent experiments (Wall & Kentala, 2005; Peterka, Wall, & Kentala, 2006). In place of center-of-gravity information from the platform, Dr. Wall substituted small inertial sensors developed by Draper Laboratory and mounted these on the torso. In the interim there has been considerable engineering work to develop sensor and tactor technologies to permit an ambulatory application of tactile feedback. Tactor configurations are explained briefly below.

The approach used in 1991 to maintain straight and level flight in an aircraft was to employ a 5 by 8 matrix of tactors around the torso at 45 degree spacing starting at the navel. The configuration of eight columns was selected to accommodate the conditions of pure pitch (fore and aft), pure roll (left and right), and combined pitch and roll (four intermediate positions on the torso). The simpler, reduced configuration of providing combined pitch and roll by using two tactors (front and back and a left and right) simultaneously did not work well since it required training and cognitive effort to become proficient. In the initial 1991 flights, the matrix employed five horizontal rows to provide the extent/magnitude of roll and pitch. When the object was simply to maintain straight and level flight (i.e., the equivalent of upright balance) only the bottom row was required which led to the development of a single belt for terrestrial

applications. The single belt was used for navigation, location of targets, and balance on the equitest platform.

The single row TSAS (1 by 8) tactor belt was selected by Karen Atkins for her doctoral dissertation at the College of Allied Health and Nursing, Nova Southeastern University. Atkins' dissertation concerned the treatment of patients experiencing balance dysfunction. Her dissertation research was designed to promote sensorimotor brain reorganization during balance exercises by providing sensitive real-time sway feedback to the patient via touch. It was hoped that this approach would exploit brain neuroplasticity by fostering sensory substitution (Bach-y-Rita, 1987), thus helping the patient return to normal postural coordination.

Although very little was known about the usefulness of tactile cueing for balance rehabilitation when Atkins started her dissertation, the rationale for the dissertation topic was strengthened by the fact that tactile cues had been shown to be localizable with certain variations in the stimulus provided or the age of the user (Cholewiak & Collins, 2003; Cholewiak, Brill, & Schwab, 2004). Also, tactile cueing had proven beneficial as an assistance device to yield acute improvement of gait (Dozza, Wall, Peterka, Chiari, & Horak, 2007) and standing balance among healthy young and old persons (Peterka, Wall, & Kentala, 2006; Verhoeff, Horlings, Janssen, Bridenbaugh, & Allum, 2009), as well as patients with central or peripheral vestibular pathology (Wall & Kentala, 2005; Danilov, Tyler, Skinner, Hogle, & Bach-y-Rita, 2007). Hence, Atkins took the next step to determine if TSAS could improve balance rehabilitation outcomes, even for those with significant problems such as stroke-related imbalance. Moreover, Atkins sought to extend the past findings from the scientific study of balance by vestibular researchers to the clinical study of balance improvement within the context of physical therapy, which is critical to the clinical transition of tactile cueing. Atkins' dissertation (Atkins, 2010) found that TSAS was beneficial for standing balance therapy and recommended further research to determine the full array of functional abilities which may be improved.

Group consideration of three tactile sway cueing approaches

The government and its partners conducted extensive hardware development and evaluation efforts prior to the successful test of the 1 by 8 tactor belt by Atkins (2010) for rehabilitation. Evaluation of the best tactile stimulus candidates occurred at a meeting held at the Institute of Human and Machine Cognition (IHMC) in Pensacola, FL in 2009. The primary goal of the IHMC meeting was to further the development of the "sensory substitution" concept as forwarded by the late Paul Bach-y-Rita. Dr. Bach-y-Rita proposed that the sense of touch could be "substituted" for the sense of vision with large arrays of stimulators on the torso to provide, for example, pictures or letters (Bach-y-Rita, 1987). A group of experts met to experience the capability of the various tactile candidate systems to improve balance among persons suffering from disequilibrium. The group consisted of Drs. Anil Raj, Fred Guedry, Wally Grant, Jan Holley, Ian Curthoys, and Angus Rupert. The three technologies evaluated included: 1) the tactile tongue interface BrainPort (Wicab, Inc., Middleton, WI); 2) the VideoTact array (ForeThought Development, LLC); 3) an in-house modified version of TSAS. The panel's thoughts are summarized below:

a. BrainPort

(1) Summary of features

(a) The BrainPort balance device is composed of two components: the intraoral device (IOD) and the controller. The IOD is made up of an electrotactile array and a MEMS 3-Axis, ± 2 grams, digital output x-y-z accelerometer (Danilov et al., 2007). A flexible cable connects the IOD to the controller. The electrically-bioisolated accelerometer senses fore-aft and lateral head position.

(b) Electrotactile stimuli are delivered to the dorsum of the tongue by the 10 by 10 element electrode array. The IOD array and tether are fabricated as a flexible circuit using industry-standard photolithographic techniques employing a polyimide substrate. One hundred conductors in the tether are connected to array electrodes, while the remaining six conductors provide power and communication links to the accelerometer. The 1.5-millimeter (mm) diameter electrodes are arranged in a square pattern on 2.32-mm centers. The array footprint is 24 by 24 mm. Each electrode isolated with a 127 nanometer (nm) thick layer of gold. The tether (12-mm wide by 2-mm thick) connects the electrode array and accelerometer to the controller. The controller contains an embedded computer (ColdFire MCF5249C, 120 megahertz [MHz], 32-bit microprocessor), stimulation circuits, user controls, and battery power supply. Custom software operating on the controller converts signals from the accelerometer in the IOD into a dynamic 2 by 2 electrode pattern of electrotactile stimulation. Control buttons allow the user to preset their own maximum stimulation intensity level.

(c) Head position information derived from the accelerometer is used to position the tactile stimulus pattern on the tongue display (electrode array). The accelerometer data is acquired at 50 hertz (Hz) for the purpose of feedback to the user. In the current implementation, mapping the 12-bit data to the 10 by 10 oral tactile array causes ‘binning’ of the output signal into 2.8-degree increments both lateral (x-axis) and anterior/posterior (y-axis) to individual tactor rows or columns, to a maximum range of ±14 degrees in each direction. Consequently, high frequency small amplitude motion signals typically stay within a bin and are not detected by the user.

(2) Strengths and limitations

(a) Strengths:

1. The tongue is more sensitive than the torso and has a large portion of the sensory homunculus devoted to processing.

2. The tongue is located very near the brain (for the most rapid possible response to sway cues).

3. Cueing systems designed for the tongue will necessarily be small and ultimately, ambulatory.

4. The tongue is both a means of sensing touch cues and a means of actively controlling assistance technologies (e.g., changing gain or sign of the system for different applications or user states), whereas the torso is more likely to be exploited for passive cutaneous sensation, or to require manual intervention for changes to the setting of the system. Hence, a tongue-based system may be well suited to situations where system settings must be changed frequently, discretely, or by a user without access to full manual control.

(b) Limitations:

1. Research indicates that factors other than distance from the brain account for the majority of variance in the literature on human reaction time (Welford, 1980).

2. The horizontal top surface of the tongue maps less intuitively to 3-dimensional external space and is a less obvious substrate for the representation of wide field flow information concerning one's body movement through space.

3. The tongue is required for taste and speech, which means that distraction may occur from these other activities when one is using the display, which requires the user to hold his or her tongue still against the device.

4. It is somewhat more difficult to create a confidential assistive device using the tongue unless the current wires going out of the mouth are engineered out of the system. Fortunately, the later model of Brainport is wireless, but even so, having a device in the mouth may feel more uncomfortable, distracting, or obvious to others than supplying the cues to some other area of the body, thereby limiting patient acceptance. Moreover, due to the tiny size of discrete stimulation points needed for a tongue array, the stimulus is usually electrotactile in nature, rather than vibrotactile. While the electrotactile application is safe and may be effective, it may be more difficult for some users to accept.

5. An important limitation to the Brainport solution are that the multi-center trials have not worked (Goebel, Sinks, Pyle, Brey, Eggers, & Zapala (2008)

6. Subsequent to the evaluations in Pensacola, the Brainport company appears to have gone out of business, which severely limits equipment procurement and transition opportunities.

(c) Caveat: It should be noted that one of the system evaluators (Raj) has had more experience and involvement with tongue-based solutions than any other solutions described in this report.

b. VideoTact

(1) Summary of features

(a) See ForeThought Development, LLC website at www.4thtdev.com/vidtech.html.

(b) A large array of 768 electrotactile tactors arranged in a 24 by 32 matrix

(c) Relatively high resolution array in thin, flexible, abdominal-mounted, laminated sheet.

(d) Camera-based. The system is designed to interface with a computer-based image-grabber board to process information from a video camera.

(2) Strengths and limitations

(a) Strengths:

1. Low power consumption.

2. Ambulatory with small computer supporting the stimulator.

3. Control of many stimulus variables: the pulse width, pulse amplitude (for each phase), inter-pulse null, and the number of pulses per burst are each independently controlled variables for each tactor.

(b) Limitations:

1. Camera-based recognition algorithms.

2. With current system, only a single plane array is available to cover the typical abdomen.

3. The primary difficulty experienced with electrotactile arrays is a result of the narrow band between the threshold for perceiving the stimulus and the experience of painful stimuli. Although this feature has been improved by maintaining a uniform contact through the use of electrode pastes, the paste itself is not readily accepted by the user community.

c. TSAS

(1) Summary of features

(a) Vibrating tactors are arranged around the torso to provide sway information via the location (sway direction) and rate of vibration (sway magnitude). The computer processor used

is 3.6 by 3.8 inches, and weighs about 3 pounds. This apparatus is fixed to the tactor belt garment, which is held on by Velcro. The belt contains the tactors, a controller, and a battery. The sites of stimulation, spacing, and number of tactors have been refined in research such as that carried out by Cholewiak, Brill, & Schwab (2004). Drawing partially from their work, we employ a single belt of eight tactors surrounding the waist for the current application.

(b) Mortimer, Zets, and Cholewiak (2007) recommend that optimal tactors should have a frequency response up to 300 Hz, a displacement output that exceeds 24 decibels (dB), and a rise time of less than 5 milliseconds (ms). They also recommend that when multiple, wearable tactors are used the tactors should be small and able to generate a highly localized, punctuate signal. Such performance is possible with Dr. Zet's C2 linear-actuated tactors to be employed in this project. The standard Engineering Acoustics, Inc, (EAI) C2 tactor design yields a rugged, low profile package with nominal center frequency of 250 Hz. The stimulus is a varying pseudo sinewave in the range of 31 to 300 Hz. The skin contactor is 0.3 inches diameter and is pre-loaded when the face of the tactor is placed against the skin. The Eval.2.0 tactor controller is an integrated control module that is capable of operating up to eight C2 tactors. The controller can be battery operated and is directly addressed via a RS232 serial or USB interface, using standard software protocols. Optional features include a Bluetooth wireless adaptor and additional on-board memory using a secure digital (SD) memory card. The Eval.2.0 controller is able to activate single or multiple C2 tactors under software control. Predefined tactile patterns ("sequences") can be stored in the on-board memory and activated with a single command. Multiple boards may be connected together in a master-slave configuration, capable of controlling up to 64 tactors. EAI's Eval.2.0 interface/controller is intended as a commercial off-the-shelf solution to a wide variety of tactile applications, and is well-suited for the current application.

(2) Strengths and limitations

(a) Strengths:

1. The torso is relatively stable and has a large area dedicated to touch sensation and thus free for the processing of artificial tactile cues that can easily be exploited for a wide range of applications beyond the simple cueing of sway in the horizontal plane such as would be possible using a display on top of the user's tongue (e.g., torso cueing readily can be used to aid control of descent and ascent during vertical motions).

2. While tongue sensations are primarily used to control tongue movement relative to the teeth, palate, and lips (for speech or to assist with eating), torso skin sensations are used for tasks which have more obvious relevance to body-centric orientation, i.e., to spatially map the location and motion of the body in space (e.g., pressure on the back in different orientations or during different accelerations) or of objects on the body (e.g., a mosquito).

3. It is feasible to create a confidential assistive device using the torso. A solution involving vibrotactile stimulation to the torso is likely to be accepted by patients, provided it is easy to don, comfortable to wear, and not too noisy or distracting.

(b) Limitations:

1. The vibrotactile actuators are acoustically louder and use more energy than electrotactile solutions.

2. The vibrotactile device is larger than electrotactile solutions.

(c) Caveat: As noted earlier in this report, the first author (Rupert) has had more experience and involvement with TSAS-based solutions than any other solutions described in this report.

Outcome of the initial group evaluation and subsequent developments

The group of six evaluators (which included the first author) concluded that, of the three displays evaluated above, the TSAS display was most ready for further study. As a result of the evaluations, a single row array was developed by the U.S. Navy and supplied to the U.S. Army Aeromedical Research Laboratory (USAARL) for flight applications (called "TSAS Lite") and to the USAF for navigation and triage (Marco Polo program). Units were also loaned to several universities for evaluation. One loaned unit was a single-row vibrotactile device selected by Dr. Atkins for her dissertation work on balance rehabilitation following brain injury. This technology has proven to be beneficial for rehabilitation of balance following certain kinds of brain injury.

Other efforts are underway to determine the best use of this device. The various academic, commercial, and military efforts described in this report are yielding important technology transitions. The prototype rehabilitation technology, developed by Electrical Acoustics Engineering and partly an offshoot of DoD-funded programs to reduce aviation disorientation mishaps, is now being improved to serve as a fully functional clinical device ready for field use. This report concludes by identifying some key transition areas and by listing our recommendations for the next steps in development.

One application of this device would be to assist military personnel experiencing mild traumatic brain injury (mTBI) following exposure to improvised explosive devices (Lawson & Rupert, 2010), the majority of whom show evidence of vestibular pathology (Balaban & Hoffer, 2009; Hoffer, Gottshall, Balaban, & Balough, 2010). The rehabilitation technology described herein should aid wounded warriors as well as other patients whose balance has been disrupted by causes not restricted to explosions, such as labyrinthine disorders, diabetes, sports injuries, traffic injuries, injuries associated with experience as a prisoner of war (Sausen, Clark, Ambrose, Mitchell, Stiney, & Bower, 2001), or normal sensory degradation associated with aging (Luxon, in Baloh & Halmagyi, 1996; Baloh & Honrubia, 2001; Tanielan & Jaycox, 2008; Krejcova & Cerny, 1989; Wikstrom, Naik, Lodha, & Cauraugh, 2009; Bonnet, Carello, & Turvey, 2009). Improved measures and countermeasures are important for restoring the functional ability of patients with these problems.

Relevant work is being initiated concerning these issues by the authors of this report, EAI, and Dr. Atkin's company, BalanceSense. These efforts are supported by U.S. Army-funded projects, a congressionally-directed project, and SBIR projects. Also, a series of workshops is being initiated by the Coalition Warfare Program, which will bring together international subject matter experts to finalize the best practices for clinical implementation of the technology.

Conclusions and Recommendations

This report explored the use of tactile sway cueing as a compensatory strategy for patients suffering disequilibrium. Sway feedback systems have the potential to aid Soldiers with MTBI and other patients whose balance has been disrupted by concussions, labyrinthine diseases, or aging. Several sway biofeedback approaches were evaluated and their strengths and limitations identified. A TSAS-based system was selected for further study by the first author and five other system evaluators. The six evaluators were unanimous in their recommendations, but it should be noted that the first author (Rupert) has had more experience with TSAS-based solutions than any other solution. Recommendations are made below concerning the necessary steps remaining in the development and successful transition of this technology:

a. Develop portable balance assessment tool and tactile feedback device based on center-of gravity information from a posturography platform. Involve the PT community as the lead for more extensive and more objective comparison and modification of available approaches, leading to development and refinement of an optimized cueing device.

b. Obtain U.S. Food and Drug Administration (FDA) approval for a predicate device to deliver to the PT community for vestibular rehabilitation.

c. Develop an SBIR to incorporate audio and visual enhancements to improve the current state-of-the-art device.

d. Develop a SBIR/Small Business Technology Transfer Research (STTR) to deliver hardware permitting accurate and dynamic center-of-gravity information in real time.

e. Initiate via Army Research Office (ARO) a Multiple University Research Initiative (MURI) to begin a multisegmental postural control algorithm incorporating multisensory feedback loops as prostheses for ambulatory personnel.

f. Develop a device/application which models and simulates acute vestibular injury to permit rapid evaluation of new devices intended for treatment of mTBI.

As of the present date, the authors are involved in funded efforts addressing items a through c above and are initiating conversations and proposals geared towards items d through f. We believe that tactual sway cueing has an important role to play in future military balance testing, rehabilitation, and assistance following mTBI and are working to promote the transition of this

technology to the military and civilian sectors. Since the much larger issue of falls is partially addressed by this same assessment/rehabilitation technology, the goal is to involve other agencies, especially the National Institutes of Health, for a coordinated approach to accomplishing the above goals and recommendations.

References

Atkins, K. L. 2010. Vibrotactile postural control in patients that have sit-to-stand balance deficit and fall. (Report No. 2010-18) Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory.

Bach-y-Rita, P. 1987. Brain Plasticity as a Basis of Sensory Substitution. Journal of Neurorehabilitation and Neural Repair. 1(2): 67-71.

Balaban, C., and Hoffer, M. E. March 18, 2009. Mild traumatic brain injury: Vestibular consequences. Defense Center of Excellence Global Video Tele-Conference, Brain Injury Awareness Presentation. Retrieved October 5, 2009 from www.dcoe.health.mil/Training/GlobalVTCs.aspx

Baloh, R. W., and Halmagyi, G. M. 1996. Disorders of the Vestibular System. New York, NY: Oxford University Press.

Baloh, R. W., and Honrubia, V. 2001. Clinical Neurophysiology of the Vestibular System. 3rd ed. New York, NY: Oxford University Press.

Bonnet, C., Carello, C., and Turvey, M. T. 2009. Diabetes and postural stability: Review and hypotheses. Journal of Motor Behavior. 41: 172-190.

Brown, J. S. 2009. Evaluation of Tactile Situation Awareness System as an Aid for Improving Aircraft Control during Periods of Impaired Vision. Thesis, Naval Postgraduate School, Monterey, CA. Retrieved from http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA501130.

Cardin, S., Vexo, F., and Thalman, D. 2006. Vibro-tactile interface for enhancing piloting abilities during long term flight. Journal of Robotics and Mechatronics. 18(4): 1-11.

Cholewiak, R.W., Brill, J. C., and Schwab, A. 2004. Vibrotactile localization on the abdomen: Effects of place and space. Perception and Psychophysics. 66(6): 970-987.

Cholewiak, R.W., and Collins A., 2003. Vibrotactile localization on the arm: Effects of place, space, and age. Perception and Psychophysics. 65(7): 1058-77.

Curry, I. P., Estrada, A., Grandizio, C. M., and Erickson, B. S. 2008. Drift cues from a tactile belt to augment standard helicopter instruments. International Journal of Applied Aviation Studies. 8(1): 74-87. Retrieved from www.faa.gov/about/office_org/headquarters_offices/arc/programs/academy/journal/pdf/Summer_2008.pdf.

Danilov, Y. P., Tyler, M. E., Skinner, K. L., Hogle, R. A., and Bach-y-Rita, P. 2007. Efficacy of electrotactile vestibular substitution in patients with peripheral and central vestibular loss. Journal of Vestibular Research. 17: 119-130.

Dozza, M., Wall, C., Peterka, R. J., Chiari, L., and Horak, F. B. 2007. Effects of practicing tandem gait with and without vibrotactile biofeedback in subjects with unilateral vestibular loss. Journal of Vestibular Research. 17(4): 195-204.

Goebel, J., Sinks, B., Pyle, M., Brey, R., Eggers, S., & Zapala, D. 2008. Efficacy of the Brainport balance device in patients with severe bilateral vestibular loss: A multi-center trail. Association of Research in Otololaryngology, 31st MidWinter Research Meeting, 16-21 Feb, Phoenix, AZ. Retrieved from http://www.aro.org/archives/2008/2008_707_9ec5e61b.html.

Herdman. S. J. 1999. Vestibular Rehabilitation. 2nd ed. Philadelphia, PA: F.A. Davis, Co.

Hoffer, M. E., Gottshall, K. R., Balaban, C., and Balough, B. J. 26 January 2010. Mild traumatic brain injury: What we have learned and implications for space flight (presentation). University Space Research Association, Division of Space Life Sciences, University of Texas Medical Branch/Johnson Space Center Aerospace Medicine Residency Program, Space Medicine Grand Rounds Archive. Retrieved from www.dsls.usra.edu/archive_2010.html.

Jain, V., Wood, S. J., Feiveson, A. H., Black, F. O., and Paloski, W. H. 2010. Diagnostic accuracy of dynamic posturography testing after short-duration space flight. Aviation Space and Environmental Medicine. 81: 625-63.

Krejcova, H. and Cerny, R. 1989. Vestibular abnormalities in encephalopathia pugilistica. Acta Oto-laryngologica. 108: 209-210.

Lawson, B. D., and Rupert, A. H. 2010. Vestibular aspects of head injury and recommendations for evaluation and rehabilitation following exposure to severe changes in head velocity ambient pressure. In Proceedings of the Human Performance at Sea Symposium. University of Strathclyde, Glasgow, U.K.

McGrath, B. J., Estrada, A., Braithwaite, M. G., Raj, A. K., and Rupert, A. H. 2004. Tactile situation awareness systems flight demonstration. (Report No. 2004-10) Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory.

Mortimer, B. J., Zets, G. A., and Cholewiak, R. W. 2007. Vibrotactile Transduction and Transducers. Journal of the Acoustical Society of America. 121: 2970-2977

Peterka, R. J., Wall, C., and Kentala, E. 2006. Determining the effectiveness of a vibrotactile balance prosthesis. Journal of Vestibular Research. 16: 45-56.

Raj, A. K., Suri, N., Braithwaite, M. G., and Rupert, A. H. 1998. The tactile situation awareness system in rotary wing aircraft: Flight test results. In Proceedings of the RTO/HFM Symposium on Current Aeromedical Issues in Rotary Wing Operations. Neuilly-sur-Seine, France. RTO NATO HF, RTO-MP-Vol. 19: 16.1-16.7 (ISBN 9283700082). Presented in San Diego, CA 19-21 Oct.

Rupert, A. H., Mateczun, A., and Guedry, F. E. 1990. Maintaining spatial orientation awareness. Situation Awareness in Aerospace Operations. Copenhagen, Denmark. AGARD-CP-478: 21-1 to 21-5.

Rupert, A. H., Guedry, F. E., and Reschke, M. F. 1994. The use of a tactile interface to convey position and motion perceptions. France: AGARD, Virtual Interfaces: Research and Applications: 20.1-20.7.

Rupert, A. H. 1998. Haptics as the most intuitive spatial orientation system. In Proceedings of the 3rd Annual Symposium and Exhibition on Situational Awareness in the Tactical Air Environment. Presented in Piney Point, MD, 2-3 June.

Rupert A. H. 2000. Tactile situation awareness system: Proprioceptive protheses for sensory deficiencies. Aviation, Space, and Environmental Medicine. 71: A92-A99.

Sausen, K., Clark, M., Ambrose, R., Mitchell, M., Stiney, M., and Bower, E. 2001. Gait and balance in repatriated prisoners of war: Data from the Robert E. Mitchell Center for Repatriated Prisoners of War. Aviation, Space, and Environmental Medicine. 72: 294.

Tanielan, T., and Jaycox, L. H. 2008. (Eds.). Invisible wounds of war: Psychological and cognitive injuries, their consequences, and services to assist recovery. Rand Center for Military Policy Research. Retrieved September 21, 2009 from www.rand.org/pubs/monographs/2008/RAND_MG720.pdf.

Verhoeff, L. L., Horlings, C. G., Janssen, L. J., Bridenbaugh, S. A., and Allum, J. H. 2009. Effects of biofeedback on trunk sway during dual tasking in the healthy young and elderly. Gait Posture. 30: 76-81.

Wall, C., and Kentala, E. 2005. Control of sway using vibrotactile feedback of body tilt in patients with moderate and severe postural control deficits. Journal of Vestibular Research. 15(5-6): 313-325.

Warren, R. M., and Warren, R.P. 1968. Helmholtz on perception: Its physiology and development. John Wiley and Sons: New York, NY.

Welford, A. T. (Ed.) 1980. Reaction Times. Academic Press: Sydney, Australia.

Wikstrom, E. A., Naik, S., Lodha, N., and Cauraugh, J. H. 2009. Balance capabilities after lateral ankle trauma and intervention: A meta-analysis. Medicine and Science in Sports and Exercise. 41: 1287-1295.

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